Passive galaxies as tracers of cluster environments at $z \sim 2$

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ABSTRACT

Even 10 billion years ago, the cores of the first galaxy clusters are often found to host a characteristic population of massive galaxies with already suppressed star formation. Here we search for distant cluster candidates at $z\sim2$ using massive passive galaxies as tracers. With a sample of ∼40 spectroscopically confirmed passive galaxies at $1.3<z<2.1$, we tune photometric redshifts of several thousands passive sources in the full 2 sq. deg. COSMOS field. This allows us to map their density in redshift slices, probing the large scale structure in the COSMOS field as traced by passive sources. We report here on the three strongest passive galaxy overdensities that we identify in the redshift range $1.5<z<2.5$. While the actual nature of these concentrations is still to be confirmed, we discuss their identification procedure, and the arguments supporting them as candidate galaxy clusters (likely mid-$10^{13}M_\odot$ range). Although this search approach is likely biased towards more evolved structures, it has the potential to select still rare, cluster-like environments close to their epoch of first appearance, enabling new investigations of the evolution of galaxies in the context of structure growth.

Key words. galaxies: clusters: general - galaxies: high-redshift - cosmology: large-scale structure of Universe

1. Introduction

Up to at least $z\sim1$, passive galaxies typically with early-type morphology dominate the high-mass end of the galaxy population, and are the best tracers of the highest density peaks in the large scale structure. The evolution of passive galaxy populations at $z\lesssim1$ – and in particular with respect to environmental effects – has been explored in detail also thanks to large spectroscopic campaigns (e.g., Kauffmann et al. 2004; Bernardi et al. 2006; Gallazzi et al. 2006, 2014; van der Wel et al. 2008; Sánchez-Blázquez et al. 2009; Kovač et al. 2014; Valentinuzzi et al. 2011; Muzzin et al. 2012). On the other hand, spectroscopy of passive galaxies at $z\gtrsim1.5$ has been until recently very difficult: in spite of several investigations pushing spectroscopic confirmation and more detailed studies to higher redshifts (e.g. Cimatti et al. 2004, 2008; Daddi et al. 2005; Kriek et al. 2006, 2009; Onodera et al. 2012; van de Sande et al. 2011, 2013; Toft et al. 2012; Gobat et al. 2012, 2013; Brammer et al. 2012; Weiner 2012; Krogager et al. 2014; Newman et al. 2014; Belli et al. 2014), sizable spectroscopic samples are still rare, and studying $z>1.5$ passive populations mainly relies on photometric samples (e.g. Wuyts et al. 2010; Bell et al. 2012; Ilbert et al. 2013; Muzzin et al. 2013a; Cassata et al. 2013). These studies show that the number density of passive galaxies rapidly falls beyond $z>1$, so that by

$z\sim2$ passive sources are no longer the dominant population even among massive galaxies. However, the observed evolution of massive cluster galaxies up to $z\sim1$ (and also theoretical models, e.g. De Lucia et al. 2006) typically suggests early ($z\gtrsim2$-3) formation epochs for their stellar populations (e.g., Mei et al. 2009; Mancone et al. 2010; Strazzullo et al. 2010). We might thus expect that the surge of passive galaxies around 10 billion years ago occurred differently in different environments.

Several recent studies have claimed evidence of significant star formation even in central cluster regions at $z\gtrsim1.5$ (among several others, Hilton et al. 2010; Tran et al. 2010; Hayashi et al. 2010; Santos et al. 2011; Fassbender et al. 2011; Brodwin et al. 2013), suggesting that indeed we are approaching the formation epoch of massive cluster galaxies. However, it is also noticeable that massive *passive* galaxies are often found even in such most distant clusters, although in many cases sharing their environment with galaxies in a still active formation phase (e.g., Kurk et al. 2009; Papovich et al. 2010; Gobat et al. 2011, 2013; Tanaka et al. 2012, 2013; Spitler et al. 2012; Strazzullo et al. 2013; Newman et al. 2014; Andreon et al. 2014). This may suggest that, even at a cosmic time when star formation rate density is at its peak (e.g. Madau & Dickinson 2014), and star formation is still active in a considerable fraction of massive galaxies (e.g. Ilbert et al. 2013; Muzzin et al. 2013a), the densest cores of
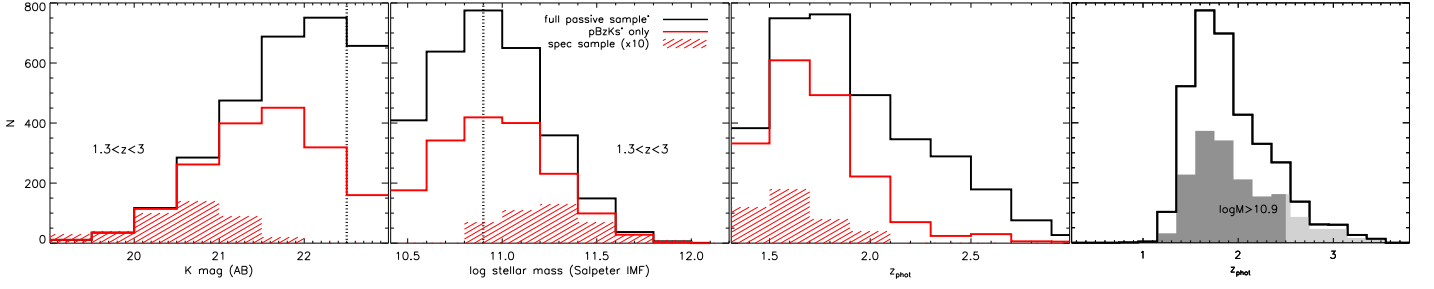
Fig. 2: Distributions of K-band magnitude, stellar mass and photometric redshift for the sample of $K_{AB} < 23$, $z > 1.3$ passive galaxies. The three leftmost panels show the full sample (see text, black line), its pBzK sub-sample (red line), and the spectroscopic sample (scaled by $\times 10$, red shaded area). Vertical dotted lines show the magnitude and mass (at $z < 2.5$) completeness limits of the parent K-selected catalog (see text). The rightmost panel shows the full photo-z distribution of the $K_{AB} < 23$ passive sample (black line), and of its $\log(M/M_\odot) > 10.9$ sub-sample (shaded area, lighter-gray at $z > 2.5$ where sample is beyond mass completeness).

most evolved cluster progenitors already host a typically small but characteristic population of massive quiescent galaxies. For this reason, overdensities of passive sources might be considered as possible signposts to clusters at least up to $z \sim 2$.

2. Photometric redshift estimation for high-redshift passive galaxies in the COSMOS field

Using one of the first sizable samples of $z \gtrsim 1.4$ passive galaxies in the COSMOS field for calibration, in Onodera et al. (2012) (hereafter O12) we could estimate more accurate photometric redshifts (photo–zs, z_{phot}) for high-redshift passive sources. We have now assembled a new, independent sample of passive galaxies in COSMOS with redshifts measured through UV features using VLT/VIMOS spectroscopy. We targeted 29 $I_{AB} < 25$ galaxies selected as passive BzKs ("pBzKs", Daddi et al. 2004, plus 6 24μm-detected pBzKs) from the McCracken et al. (2010) (hereafter M10) catalog. A redshift was measured for 34 of the 35 targets, with a robust estimate for 29 sources. The observations, analysis, and a full redshift list will be presented in Gobat et al. (in prep.). Here we focus on a sub-sample of 42 spectro-

scopically confirmed pBzKs, selected in the range $1.3 < z_{spec} < 2.1$ and with restframe UVJ colors (Williams et al. 2009) consistent with passive populations (15 and 27 galaxies from the O12 and VIMOS samples, respectively, including 3 24μm-detected sources as noted below). Fig. 1 shows the performance on this sample of our photo-zs, estimated with EAzY (Brammer et al. 2008) and calibrated as in O12. The normalized median absolute deviation (NMAD) of $\Delta z/(1 + z)$ is 2.5% on the full sample, or 1.8% excluding galaxies with less reliable z_{spec} (Fig. 1), with no catastrophic outliers (thus <2.5% for this sample). All results presented here are based on the photometric catalog by M10[1].

3. Passive galaxy overdensities at $z > 1.5$

Spectroscopic confirmation of large passive galaxy samples at high redshift is for now precluded, so we rely on passive candidates with photo-zs calibrated as above. We select a sample of $z > 1.5$ passive galaxies as follows: with an initial BzK selection on the M10 $K_{AB} < 23$ catalog, we take all pBzK galaxies, as well as galaxies formally classified as star-forming BzKs ("sBzKs") but having a S/N<5 in the B- (and possibly z-) band. From this first selection, we retain all galaxies that also have UVJ passive colors (assuming their z_{phot} as of Sec. 2). Sources detected at 24μm and satisfying the above criteria are retained, because of the possibility of AGN-powered 24μm flux. Sources with possibly contaminated IRAC photometry (as in the M10 catalog) were discarded (<10%). In Fig. 2, black and red lines show the stellar mass, K-band magnitude and photo–z distributions for the full retained sample of passive galaxies according to these criteria, and for its subsample of pBzK sources, respectively.

The $K_{AB} < 23$ limit corresponds to a 90% completeness for point-like sources, going down to ~22.5 for disk-like profiles (see M10). At $z \sim 2.5$ these limits would correspond to a mass completeness of $\log(M/M_\odot) \sim 10.8$-11 (~10.9 in the following, Salpeter (1955) IMF) for an unreddened solar metallicity Bruzual & Charlot (2003) SSP formed at $z \sim 5$. On the other hand, the combination of selection criteria adopted above is expected
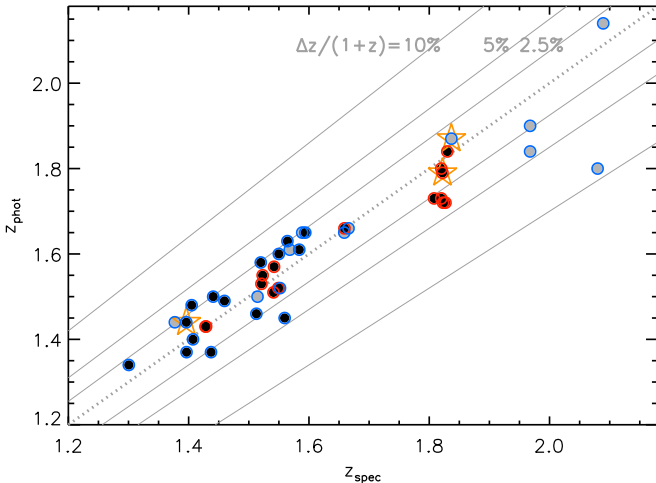

Fig. 1: Comparison of z_{phot} vs. z_{spec} for the full spectroscopic sample of $1.3 < z < 2.1$ passive galaxies. Lower quality z_{spec} determinations are shown in gray. Blue and red circles mark sources from the VIMOS and O12 samples, respectively. Orange stars highlight MIPS-detected sources. Dotted and solid lines show the bisector and a relative scatter of 2.5, 5 and 10%.

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[1] An even better photo-z accuracy (as low as 1.5%, with a marked improvement at $z \gtrsim 1.8$) can be obtained calibrating photo-zs on this sample with the more recent photometry from the Muzzin et al. (2013b) UltraVISTA catalog, in agreement with - and only marginally better than - the results obtained with Muzzin et al. (2013b) photo-zs, as will be discussed in a forthcoming paper (Strazzullo et al., in prep.). Here we use the M10 catalog which includes the southern part of the 2 sq. deg. COSMOS field where one of our overdensities (Sec. 3.1) is found, not covered by the UltraVISTA survey (McCracken et al. 2012).
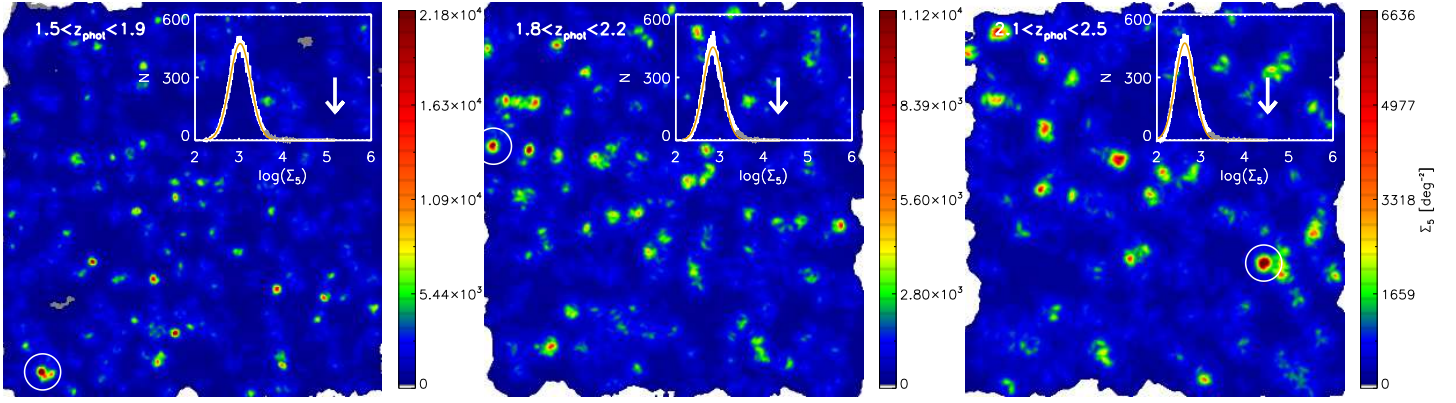
Fig. 3: Examples of Σ_5 maps in redshift slices of the full passive galaxy sample in the 2 sq. deg. COSMOS field (North is up, East is left). Maps are scaled so that red colors correspond to $> 5\sigma$ significance. The three candidate overdensities described in Sec. 3.1 are highlighted with white circles (2 Mpc radius proper). In each plot, the inset shows the distribution of $\log(\Sigma_5)$ values in the map and its gaussian fit (white and orange lines, respectively), and the white arrow shows the peak Σ_5 value of the highlighted overdensity.

to result in a largely pure (in terms of contaminants) but *not complete* sample of massive ($\log(M/M_\odot) \gtrsim 10.9$) passive galaxies. For this reason, we may be missing some overdensities or reducing their significance, which would affect in a conservative way the results presented here. The BzK selection, and the depth of the M10 catalog, effectively limit our sample at $z > 1.5$ and $z < 2.5$, respectively (Fig. 2, right). The full sample of $K_{AB} < 23$ passive galaxy candidates includes ~ 4500 sources. Of these, ~ 3500 are at $1.5 \leq z_{phot} \leq 2.5$ ($\sim 70\%$ at $\log(M/M_\odot) > 10.9$, $\sim 50\%$ selected as pBzK, $\sim 10\%$ 24μm-detected).

3.1. Identification of cluster candidates

We build local density maps for the full COSMOS field in redshift slices, based on the catalog of passive galaxy candidates described above. In spite of the quoted $\sim 2\%$ photo-z relative accuracy (by comparison with spectroscopic redshifts, Sec. 2), we need to consider that the spectroscopic sample is very biased towards brighter, lower-redshift sources (Fig. 2), thus photo-z performance on the bulk of our sample is likely significantly worse. We estimated a more realistic photo-z accuracy as a function of magnitude, recalculating photo-zs on SEDs of well-fitted spectroscopic sources ($|\Delta z|/(1+z) < 2.5\%$) dimmed to fainter magnitudes, randomly scattering fluxes in the different bands according to photometric errors in our catalog. This simulation indeed gives a photo-z accuracy $< 2.5\%$ at $K_{AB} \lesssim 21$ (Sec. 2), but rising to $\sim 3.5\%$ (5%) at $K_{AB} \sim 22$ (22.5), and to more than 6% approaching our $K_{AB} \sim 23$ limit. These estimates are "model-independent" in the sense that they use observed (rather than synthetic) SEDs, but they still assume that SEDs of less massive and/or higher redshift sources in our sample behave similarly to those of the spectroscopic sources used as inputs in the simulation. For comparison, the formal 68% errors estimated by EAzY on the simulated SEDs would be on average 40-50% larger (reaching $\sim 8\%$ at $K_{AB} \sim 23$). For this reason, we build our density maps in redshift slices of $\Delta z = \pm 0.2$ (corresponding to a $\pm 1\sigma$ relative accuracy of 6-8% at $1.5 < z < 2.5$) with a step of 0.05 in central redshift.

We use the Σ_5 (5th nearest neighbour) density estimator, which for our sample probes a median (over the full map) distance of ~ 1.4 Mpc in the $z \sim 2$ slice, with minimum and maximum distances of 100-200 kpc and 4-5 Mpc in all redshift slices, thus properly probing the typical scales we are investigating. For comparison, a Σ_3 estimator would also probe such scales (median distance ~ 1.1 Mpc at $z \sim 2$, minimum/maximum distances

~ 50 kpc and 3-4 Mpc), while Σ_7 would probe median distances closer to 2 Mpc with minimum/maximum of 0.5/4.5 Mpc at $z \sim 2$, thus becoming less sensitive to the scales we need to probe. Fig. 3 shows three examples of Σ_5 maps. For each map, we estimate the significance of overdensities by fitting the distribution of $\log(\Sigma_5)$ in the whole map with a Gaussian (Fig. 3).

At the same time, we also use an independent approach to search for concentrations of massive passive galaxies with consistent photo–zs in a very small cluster-core sized area. In particular, based on observations of the $z = 2$ cluster Cl J1449+0857 (Gobat et al. 2011, 2013; Strazzullo et al. 2013, other examples in Sec. 1), we search our $\log(M/M_\odot) > 10.9$ passive sample for sources with at least three other passive galaxies within $|\Delta z|/(1+z) < 7.5\%$ (accounting for photo-z uncertainties described above) and a physical distance ≤ 150 kpc[2]. This approach independently retrieves three most significant ($\gtrsim 7\sigma$ in the Σ_5 - as well as Σ_3 - maps) overdensities highlighted in Fig. 3, and described here below:

• CC1002+0134 at $1.5 \lesssim z_{phot} \lesssim 1.8$ – A concentration of passive sources around RA, Dec $\sim 10^h 02^m 40^s$, $+01°34^m 20^s$, with 4 galaxies within a radius $r = 90$ kpc and z_{phot} within $\leq 1.5\sigma$ (given each source magnitude, based on the simulation described above) from a mean $z_{phot} \sim 1.76$. However, the photo-z distribution of the central sources in this candidate overdensity is quite broad compared to the expected photo-z uncertainties (see Fig. 4). This might suggest a chance superposition of passive galaxies, or possibly of different, unrelated structures, along the line of sight at $1.5 < z < 1.8$. On the other hand, Aravena et al. (2012) already reported the identification of a candidate cluster at $z_{phot} \sim 1.55$ at the same position, based on an overdensity of galaxies with $1.5 < z_{phot} < 1.6$, a radio source at a consistent redshift, a tentative detection of extended X-ray emission, and the presence of a small population of passive sources. The actual nature of this structure is thus still unclear.

• CC1003+0223 at $z_{phot} \sim 1.90$ – A concentration of 4 passive galaxies at RA, Dec $\sim 10^h 03^m 05^s$, $+02°23^m 24^s$ within $r < 110$ kpc and z_{phot} within $\lesssim 1.4\sigma$ from the mean z_{phot} (a further galaxy with z_{phot} consistent within 1σ is found at $r < 340$ kpc). Half of these 4 sources were selected as UVJ-passive sBzKs (see Sec. 3). None

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[2] Based on our sample of $\log(M/M_\odot) > 10.9$ passive galaxies, the Poissonian probability of finding ≥ 3 neighbours at ≤ 150 kpc (or ≥ 4 sources within a radius of ≤ 150 kpc) with a $|\Delta z|/(1+z) < 7.5\%$ is $< 5 \times 10^{-4}$ ($< 2 \times 10^{-7}$, respectively) at all redshifts probed.
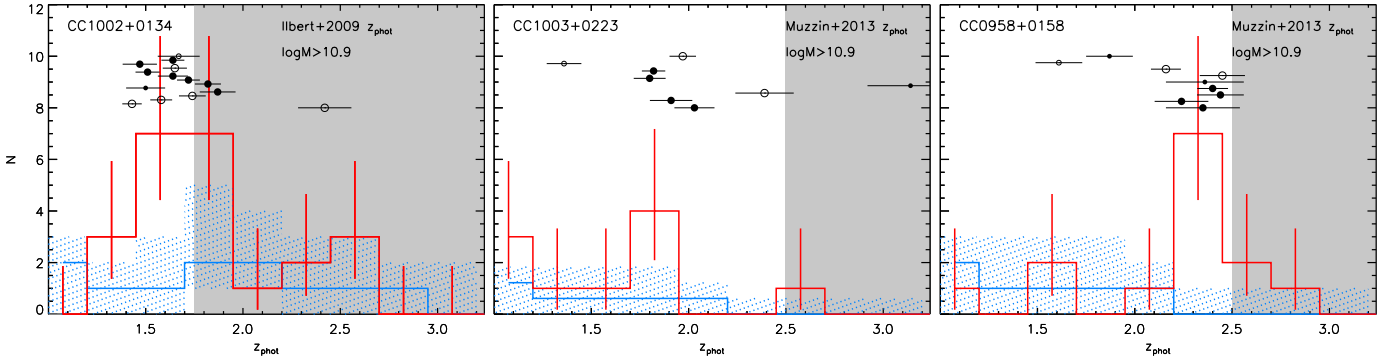
Fig. 4: Photo–z distributions for the *whole* (passive and star-forming) population of $\log(M/M_\odot) > 10.9$ galaxies within an aperture of $r < 600$ kpc from the three passive overdensities as labeled (red lines, errors as from Gehrels 1986). Galaxies and photo–zs used here are from Muzzin et al. (2013b) for CC1003+0223 and CC0958+0158, and from Ilbert et al. (2009) for CC1002+0134 (see text). In each panel, the blue line and dotted area show the median and $16^{th} - 84^{th}$ percentiles of the photo–z distribution (from the same catalogs) in $r < 600$kpc apertures at 100 random positions in the COSMOS field, while the grayed-out region shows the redshift range where the sample is no longer mass-complete. Black filled (empty) circles scattered above the histograms (at random y-axis coordinates) show *our photo-z determinations for the passive sample used in this work* within 300 kpc (600 kpc) from the overdensity center (larger/smaller symbols show galaxies more/less massive than $\log(M/M_\odot)=10.9$).

is 24μm detected. All are consistent with being UVJ-passive also in the Muzzin et al. (2013b) catalog, three out of four with a photo-z consistent within 1σ with the mean z_{phot} estimated here. The redshift distribution of the central sources is consistent with the presence of a single structure. Another overdensity of similar significance at a consistent photo-z is visible in the Σ_5 map at < 4 Mpc West (Fig. 3).

• CC0958+0158 at $z_{phot} \sim 2.35$ - A concentration of 4 passive galaxies at RA, Dec$\sim 9^h58^m53^s$,+01°58^{m}01^s within $r<130$ kpc and a z_{phot} within $\lesssim 0.8\sigma$ from the mean z_{phot} (one further, lower-mass galaxy at the same z_{phot} is found at $r<290$ kpc). Given their redshift (thus faintness) all of these sources were selected as UVJ-passive sBzKs (see Sec. 3). One might be associated with a 24μm detection. All are consistent with being UVJ-passive also in the Muzzin et al. (2013b) catalog, with photo-zs consistent within 1σ with the mean z_{phot} estimated here. The photo-z distribution is very compact, consistent with a single structure. An overdensity at a consistent position and redshift is also visible in Scoville et al. (2013) density maps. We also note the proximity of the Spitler et al. (2012) cluster candidate at similar redshift, ~ 14 Mpc NE. Chiang et al. (2014) also claim the presence of several proto-cluster candidates within a few Mpc of CC0958+0158 at a similar photo-z.

In Fig. 4 we show for comparison the photo–z distribution of a mass-limited sample of the *whole* (passive and star-forming) galaxy population in the surroundings ($r < 600$ kpc) of each passive overdensity, with respect to the distribution in same-size apertures at 100 random positions in the COSMOS field. These distributions in Fig. 4 are based on public galaxy catalogs and photo-z determinations, totally independent from those we use in this work. For CC1003+0223[3] and CC0958+0158 we use the Muzzin et al. (2013b) UltraVISTA catalog, while for CC1002+0134 - not covered by the UltraVISTA survey - we use the Ilbert et al. (2009) catalog (note that this is an *i*-selected catalog, thus not optimal in this redshift range, as shown by the gray region in Fig. 4, left). We also show in Fig. 4 *our* photo-z

determinations for *our passive galaxy sample* around the overdensities in the same aperture and mass range. Although clearly affected by limited statistics, Fig. 4 shows the correspondence between *our* photo-zs of *passive* sources identifying the overdensities, and the excess in the redshift distribution from *completely independent* photo-z determinations of the *whole* galaxy population in their surroundings.

4. Discussion and summary

This letter investigates the possible identification of first cluster-like environments using evolved galaxy populations as tracers of an early-quenched cluster core. We described the identification of 3 candidate overdensities of passive galaxies, selected in redshift-sliced density maps and with properties similar to passive galaxy concentrations in $z\sim 2$ clusters. This study relies on accurate photo-z determination for high-redshift passive sources calibrated on one of the largest spectroscopic samples available to date. We present here only the first results on the strongest candidate overdensities. Further investigation focusing on alternative sample selections and the identification of lower-mass structures, with improved photo-zs based on more recent, deeper photometry (Sec. 2), will be presented in a forthcoming paper.

We currently have no proof that the candidate overdensities we identified are real structures. Even if they were actually clusters, their expected mass and redshift would put them beyond reach of the Chandra C-COSMOS (Elvis et al. 2009) and XMM-Newton (Hasinger et al. 2007; Cappelluti et al. 2009) programs in COSMOS, which place 3σ limits of 4-9$\times 10^{43}$ erg s^{-1} on their X-ray luminosity, thus 5-7$\times 10^{13}$M$_\odot$ on their mass (Leauthaud et al. 2010). This would be consistent with their similarities with the passive concentration in Cl J1449+0857 (M$\sim$ 5 $\times 10^{13}$ M$_\odot$, Gobat et al. 2011, 2013; Strazzullo et al. 2013). As a reference, in a WMAP7 (Komatsu et al. 2011) cosmology we expect to find $\sim$2-8 structures more massive than 5-7$\times 10^{13}$ M$_\odot$ in the 1.7<z<2.5 range in a 2 sq. deg. field (or a factor $\sim$2 higher with a Planck cosmology, Planck Collaboration et al. 2014).

A final confirmation necessarily relies on spectroscopic follow-up, which is not available yet. For the time being, just for the most distant of our candidate overdensities, covered by the outer part of the zCOSMOS-deep survey (Lilly et al.

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[3] This overdensity is at the edge of the area probed by our catalog (see Fig. 3). For this reason, the $r < 600$ kpc aperture is not fully covered by the catalog; the field distribution in Fig. 4 is thus scaled accordingly, by the effectively covered area.
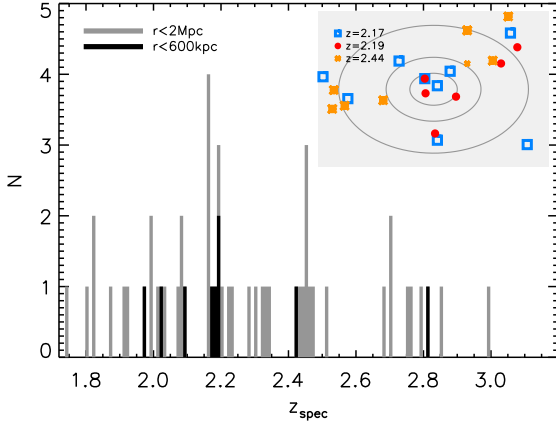
Fig. 5: The distribution of spectroscopic redshifts around the CC0958+0158 overdensity (see text). The gray and black histograms show the distribution within 600 and 2000 kpc, respectively. The inset shows the spatial distribution around the overdensity center of galaxies within $\Delta z \sim 0.1$ (or $\Delta z \sim 0.2$, smaller symbols) of the three spikes at $z \sim$2.17, 2.19 and 2.44, as indicated. The three gray circles have radii of 0.5, 1, 2 Mpc proper.

2007, and in prep.) and by a Subaru/MOIRCS spectroscopy program (Valentino et al. 2014), we have been able to combine available spectroscopic redshifts – all of star-forming galaxies – to tentatively probe the redshift distribution in its surroundings. This small, *a-posteriori*-assembled spectroscopic sample, is hampered by poor sampling of the central, densest cluster-candidate region, and sub-optimal target selection. Nonetheless, a possible redshift spike appears at $z \sim 2.19$ with 5(3) galaxies at $2.18 \lesssim z_{spec} \lesssim 2.2$ within $\sim$1600 (500) kpc from the overdensity center, plus two more spikes of galaxies within 2 Mpc of the center, at $z \sim 2.17$ and $z \sim 2.44$ (6 and 5 galaxies within $\Delta z \sim \pm 0.01$, respectively, Fig. 5). Although the spikes contain a similar number of galaxies, their spatial distribution (Fig. 5) might suggest that the passive overdensity is more likely at $z \sim 2.2$. Even if somewhat lower than the estimated photo-z of the passive galaxies, this would be anyway consistent within the uncertainties.

Dedicated follow-up work is obviously still needed to verify whether these candidate overdensities are indeed signposts for early cluster environments. If successful, this approach would provide a further option to extend the investigation of distant cluster-like structures to the $z \sim 2 - 2.5$ range. In comparison with most other (proto-)cluster search techniques at these redshifts, e.g. the "IRAC selection" (e.g., Papovich et al. 2010; Stanford et al. 2012), targeted searches around radio-galaxies (e.g., Venemans et al. 2007; Wylezalek et al. 2013), 3D mapping (with spectroscopic or photometric redshifts, e.g., Diener et al. 2013; Scoville et al. 2013; Chiang et al. 2014; Mei et al. 2014), or – closer to what done here – overdensities of optically red galaxies (e.g., Andreon et al. 2009; Spitler et al. 2012), the approach discussed in this work is likely to favour, by definition, the most evolved environments, allowing a better probe of the diversity of cluster progenitors at a crucial time for the formation of both clusters and their massive galaxies.

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